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CONTINUOUS SIMULTANEOUS REGISTRATION OF SWEATING AND BLOOD FLOW IN A SMALL SKIN AREA

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6570th AEROSPACE MEDICAL RESEARCH LABORATORIES
AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Contract Monitor: John F. Hall, Jr.
Project No. 7222, Task No. 722204

(Prepared under Contract No. AF 33(616)-7077
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FOREWORD

The work described in this report was done in the Physiology Laboratories of the St. Louis University School of Medicine in partial fulfillment of Contract AF 33(616)-7077, Project No. 7222, titled "Biophysics of Flight," and Task No. 722204, titled "Human Thermal Stress," administered by the 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio. Mr. John F. Hall, Jr., Chief, Biothermal Section, Biophysics Branch, Biomedical Laboratory, served as contract monitor.

Additional support in the performance of this work was received from the U.S.P.H.S. in Grant H-4939.

This investigation began in November 1961 and was completed in November 1962.

ABSTRACT

The report presents a capsular method for recording evaporation from a small skin area (5, 10, or more cm^2), continuously, quantitatively and with a very fast response time as brief as 0.15 seconds. Water of diffusion at rates of 0.005 $mgm/cm^2/min.$ or high sweating rates were measured with equal ease. The method is combined with photoelectric recording of the skin pulses to provide precise temporal relations of cutaneous vascular events and of sweating in the same segment of skin. Cycles of sweating in forearm skin occurred synchronously with digital vasoconstrictions but were not accompanied by changes in the rate of blood flow in forearm skin although venoconstriction in the forearm often took place with an increase in sweating. The observation contradicted the concept of bradykinin as an important vasodilator in accounting for cutaneous vasodilatation during heat stress.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

Jos M Quashnock

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INTRODUCTION

Relations between the onset and increase in sweating and cutaneous vasodilatation have been examined in previous reports from this department (ref. 1, 2, 3, 4, 5). Because of the importance of these relations to concepts of the regulation of body temperature during heat stress and to the circulatory responses which are elicited by heat, further study is indicated by methods which permit quantitative continuous registration of sweating and cutaneous blood flow in the same skin area. This report represents a procedure for such registrations.

Three different procedures which have been utilized by others for the detection of sweating were considered in relation to these needs. In one type of observation, the humidity of a still atmosphere immediately above the skin was recorded by a suitable sensor (ref. 6). Although the sensitivity of this procedure was sufficient to measure insensible perspiration, it depended on the diffusion of water vapor over a considerable distance and therefore seemed unsuited to following active sweating particularly at high rates. Further, the time constant was too long to permit precise determinations of temporal relations between sudomotor and vasomotor responses. In a second type of procedure, the changes in the water content of a dry gas passing over the skin were detected by a device sensitive to water vapor (ref. 7, 8, 9, 10, 11, 12). If the rate of gas flow was kept constant and known, the output of the sensor was proportional to the water transfer from the skin to the gas. A third procedure was actually a variant of the second except for the arrangements for changing the rate of gas flow so that its humidity remained constant (ref. 13). However, the servomechanisms used to vary the gas flow introduced a slow response in the system as well as expensive complicated apparatus. Review of these various methods did not assure that the requirements stated above would be met satisfactorily. It seemed worthwhile to develop another method for recording water movement from the skin. The procedure which is described in this report proved to be capable of recording quantitatively and continuously all rates of water movement from the skin without disturbing the subject, for as long periods as the observer might desire, and with a sufficiently rapid response to permit study of sudomotor reflex time and similar items. However, the method does have the one unsatisfactory feature of a nonlinear output from the sensing element.

The cutaneous blood flow was estimated continuously by recording the cutaneous opacity pulses as described in a previous report (ref. 14). Refinements in the design and construction of the photoelectric photometer resulted in greater sensitivity and better mounting on the skin.

Method of Registration of Regional Sweating

The uptake of water by a dry gas passing over the skin surface was detected by a small resistance element* which was sensitive to humidity. As the concentration of water vapor rose in the gas passing over this sensor, its resistance fell through several decades (e.g., from 1 x 10^9 to 1 x 10^6 ohms). This very large change in resistance permitted correspondingly large signals for electrical recording, but the logarithmic relations of the sensor's resistance to humidity complicated the reading of the records. This difficulty was of little consequence in some types of observations as in the detection of the onset of sweating or in the recording of cycles in sweating. A log voltmeter converter with a range of 3.5 decades** permitted registration of sweating over a considerable range on nearly linear ordinates when using the Humistor as the sensing element. This amplifier could be used with either a.c. or d.c. circuits. The sensor could be either an arm of a bridge circuit or part of a potential divider and the circuit excited either by alternating or direct currents. The latter result in polarization of the sensor, but are simpler to use at high resistances where polarization is slight.

In the use of alternating current circuits, the capacitative reactance of the connecting cable between the Humistor and input stage of an amplifier acts as a shunt of the high resistance of the Humistor and limits the latter's use as a detector of humidity to the higher levels. This difficulty was avoided by mounting a triode amplifier (RCA Nuvistor) on the capsule illustrated in figure 2, directly above the Humistor and correspondingly reducing the length of the wire connections. In an alternative procedure, the gas outlet of this capsule was connected to a tube in which a Humistor was mounted with short electrical connections directly to the amplifier placed above it. With these modifications, the a.c. circuit indicated the fall in resistance of the Humistor from 10^{10} ohms to lower values as well as did the d.c. circuit. However, the tubular connection between the capsule and a separately mounted Humistor did increase the time lag in the response of the Humistor to a change in sweating.

* Model HLVC - 150 log voltmeter-converter. Houston Instrument Corporation, Bellaire 101, Texas.

** Humistor, manufactured by Conrad-Carson Electronics, Inc., El Cajon, California.

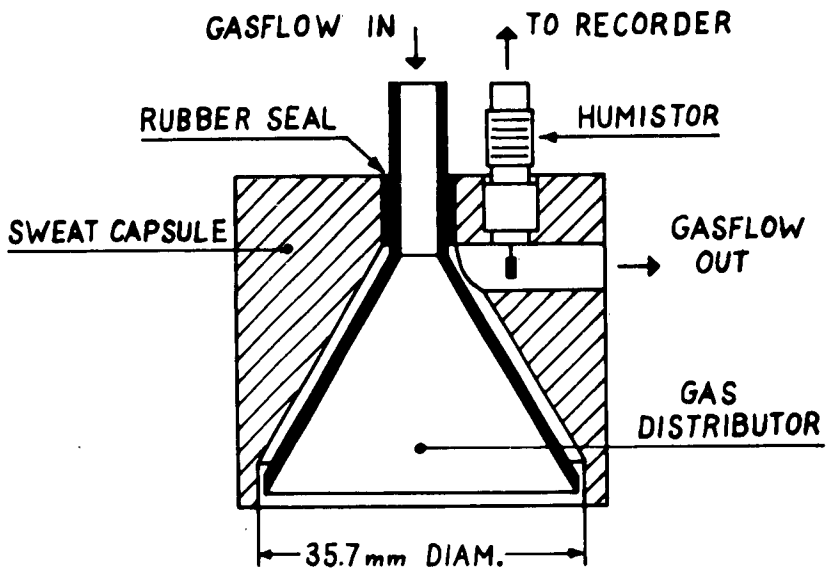

Figure 1. Design of a sweat capsule allowing a cutaneous evaporative surface of 10 cm^2. The dry gas entered above, passed down inside the inner cone, spread over the skin and flowed up in the space between the two cones to the exit part in which was mounted the sensor (Humistor).

Figures 1 and 2 show the designs of two capsules which were constructed for the measurement of evaporative rates on small skin areas. The capsules consisted of two plastic cones, one placed inside the other. The dry gas, oxygen, entered at the top of the inner cone and flowed down to the skin which lay just below the rim of the inner cone, spread over the skin surface, and escaped beneath the inner cone's rim into the space separating the two cones, and then passed up this space through the sensor's compartment to the exterior. The outer cone's rim was in contact with the skin. A tight or secure seal here was not essential, except with respect to the time constant of the unit, since only a sample of the gas passing into the intercone space was required for recording. The dead space between the sensor and the skin surface at the base of the inner cone was about 0.5 ml in the case of the larger capsule (figure 1). Therefore, with a gas flow of 200 ml/min., the lag time was about 0.15 second when the rim of the outer cone was sealed tightly to the skin. The lag

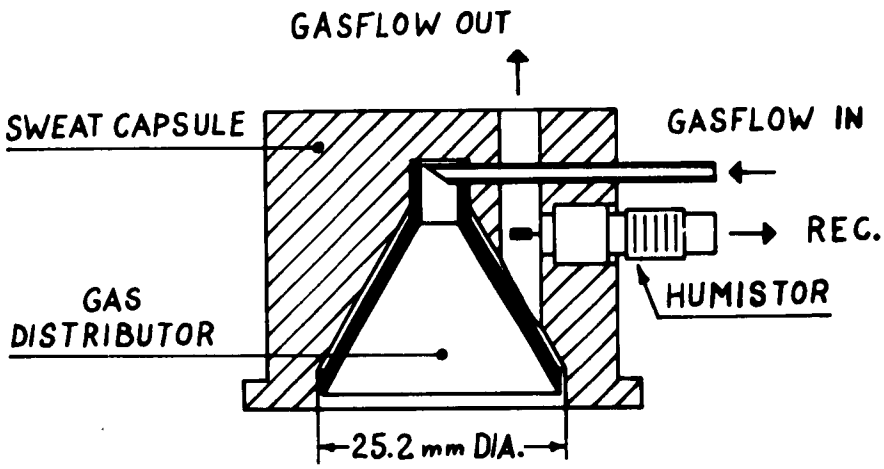

Figure 2. Another design of the sweat capsule covering a smaller skin area (5 cm^2) than that of figure 1.

time may be decreased either by making smaller capsules as illustrated in figure 2 or by using higher rates of gas flow. The high sensitivity and practically instantaneous response of the sensor permitted as high rates of gas flow as other factors made practicable.

Since the water content of gas passing over the skin surface depended on the rates of the gas flow and of evaporation of water from the skin, it was necessary to adjust the gas flow as sweating increased if the relative humidity of the gas were to remain below 90% which was the practical upper limit for the relation of the sensor's resistance to humidity. A practical compromise was attained by using only two rates of gas flow, 20 $ml/cm^2/min.$ for sweating rates below 0.4 $mgm/cm^2/min.$ and 60 $ml/cm^2/min.$ for higher sweating rates.

The accuracy with which evaporative rates could be measured with this capsular method was examined in vitro by means of the arrangement shown in figure 3, which permitted comparisons of the gravimetric estimates of evaporation with those calculated from the resistance of the Humistor. The capsule was mounted on the lower vessel in a manner to mimic its placement on the skin. The rate of escape of water molecules from the liquid surface was controlled by means of metal diaphragms which had been drilled with holes of various sizes. This procedure provided corresponding differences in the size of the wetted area. The entire arrangement was mounted on a balance and the change in weight was measured during selected

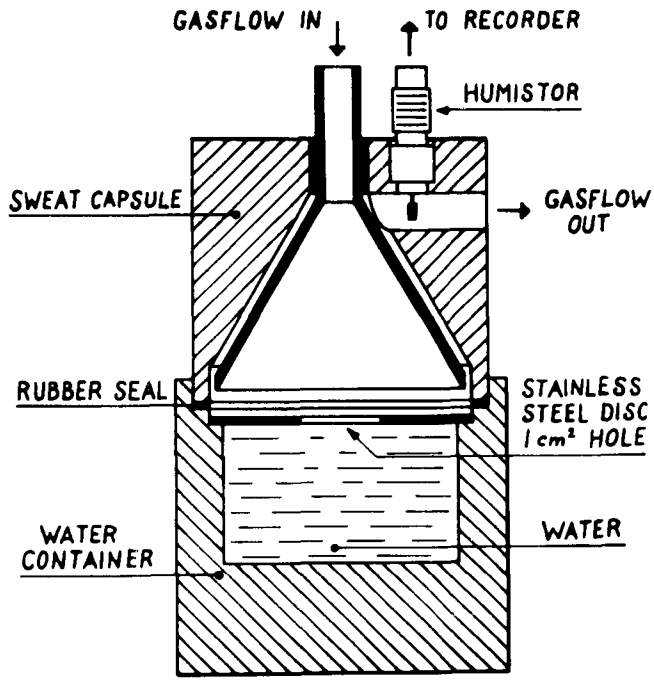

Figure 3. Arrangement for calibrating the performance of the sweat capsule. The entire device was mounted on the pan of an analytical balance and changes in weight were recorded periodically. Rate of evaporation was controlled by steel discs with holes of varying sizes.

periods of time while the dry gas flowed at a constant and monitored rate through the capsule. The manufacturer's calibration curves for humidity versus the sensor's resistance agreed with the gravimetric estimates of humidity.

Contact of the Humistor bead with dirt, salt of sweat and other substances changed its resistance when exposed to a given humidity. Washing of the Humistor with distilled demineralized water followed by drying usually restored its resistance to the original value.

Precise control of the rate of gas flow, so essential to the accuracy of the method, was assured by supplying oxygen from its tank at a pressure of about 150 mm Hg to a micrometer control valve with which final adjustment of the oxygen flow was made to the desired level. The rate of flow was monitored by a rotameter or an orifice meter with a strain gauge as the sensor. Once the desired rate of gas flow had been obtained by means of the micrometer valve, further adjustments were seldom required during the course of an experiment.

The temperature of the mixture of oxygen and water vapor passing over the sensor might affect readings of humidity in several ways: changes in kinetic energy of the water molecules, expansion or contraction of the volume occupied by them, sensitivity of the sensor to its own temperature. From the gas laws, it may be shown that in an open system such as that of the capsule, the effect of a rise in temperature on the number of collisions of water molecules with the sensor bead is negligible since expansion of the gas volume occupied by the water molecules offsets their increased velocity with rise in temperature. The arrangement shown in figure 3 permitted examination of the effect of temperature on the resistance of the Humistor at a particular humidity. The temperature coefficient thus determined appeared to be negligible in the study of sweating responses.

RESULTS

In a previous report (ref. 5) the skin resistance method was used to detect the onset of sweating and reference was made there to comparisons of that method with the capsule method described in the present report. The latter method quite consistently detected an increased movement of water to the skin surface slightly earlier than did the resistance method.

When the capsule is placed on the skin of the nonsweating subject, the resistance of the sensor increases for several minutes, finally stabilizing at a level indicative of water of diffusion at a rate of about 4 $gm/M^2/hr$. The initial period of drying probably involves water lost from the hydrated epithelium.

Cycles in sweating have been observed by many investigators. Their relations to cutaneous vasomotor activity have considerable theoretical interest. Figure 4 shows a section of a continuous recording of sweating on the forehead and forearm and of the skin pulses in the finger pad, forehead, and forearm. This recording was selected because it shows the typically simultaneous cycling of sweating in these two regions and the independence of the rates of cutaneous blood flow of the sweating cycles in the same regions. Often, but not always, the increase in sweating in one of these cycles occurred at the same time as a vasoconstriction took place in the finger pad. It was often possible to elicit increased sweating and digital vasoconstriction by presenting a stimulus such as a loud noise or a command to sweat. To what extent the orienting reflex (ref. 15, 16) is responsible for such cycles remains to be determined.

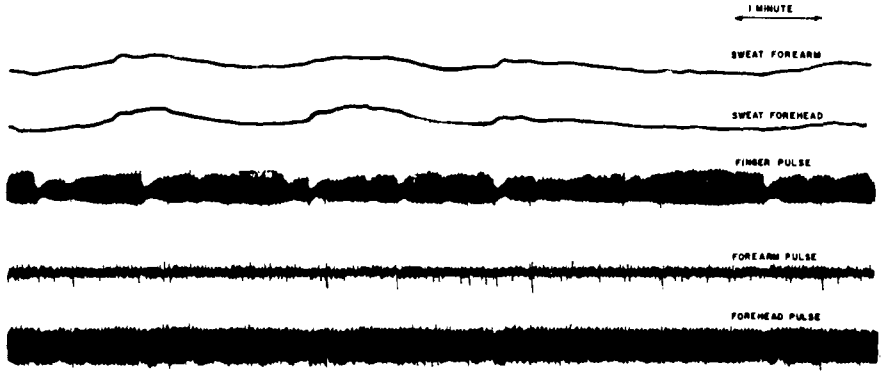

Figure 4. A section of a continuous recording of sweating on the forearm and forehead and of the skin pulses in the finger pad, forearm, and forehead.

The failure of arterial dilatation or constriction to occur in forearm or forehead skin during these sweating cycles was the rule rather than the exception. The precision of these observations casts doubt on the role of bradykinin as a principal determinant of cutaneous vasodilatation during heat stress (ref. 17). Also, such recordings illustrate the possibility of selective independence of vasomotor and sudomotor controls in the skin. An earlier proposal that the thermostatic center "hunts" in a cyclic manner (ref. 18) would be difficult to reconcile with the failure of changes in cutaneous arterial tone to accompany the sweat cycles if both cutaneous blood flow and sweating were determined by the hypothalamic center. Instead, the "hunting" attributed to this center on the basis of digital vasomotor waves and corresponding changes in heart rate may represent the unrecognized actions of the orienting reflex.

An interesting feature of the cutaneous vascular system during these cycles in sweating was the frequent occurrence of venoconstriction in the forearm skin when digital vasoconstriction accompanied the sweat cycle. This point will be discussed in a later report.

The application of these procedures is feasible when the subject is immered in water as well as in air. It is therefore now possible to observe the regional cutaneous thermoregulatory responses in a wide range of circumstances and possibly to distinguish the cutaneous autonomic components of the subject's reactions to several stressful conditions apart from those more directly related to the effects of heat.

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